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Context-dependent lightness affects perceived contrast

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ABSTRACT

Perceived contrast of a grating varies with its background (or mean) luminance: of the two gratings with the same photometric contrast the one on higher luminance background appears to have higher contrast. Does perceived contrast also vary with context-dependent background lightness even when the luminance remains constant? We investigated this question using a stimulus in which two equiluminant patches ("context squares", CSs) appear different in lightness. First we measured the lightness effect in a behavioral experiment. After ensuring that it was present for all participants, we conducted perceived contrast experiments, where participants judged the contrast of rectified incremental and decremental square-wave gratings superimposed on the CSs. For the incremental gratings participants' settings were significantly different for the two CSs. Specifically, perceived contrast was higher when the gratings were placed on the context square that was perceived lighter. In a follow-up experiment we measured perceived contrast of rectified gratings on isolated patches that differed in luminance. The pattern of results of the two experiments was consistent, demonstrating that possibly shared mechanisms underpin the effects of background luminance and context-dependent lightness on perceived contrast.

1. Introduction

By now it is well established that the human visual system is not primarily concerned with estimating the physical and optical properties of images formed on the retina. Instead it seems to be more interested in estimating object and scene properties that are critical for the fitness of the organism (see e.g., Koenderink, 2012; Purves, Morgenstern, & Wojtach, 2015). While how the visual system accomplishes this remarkable feat given a pair of inherently ambiguous retinal images is far from being completely understood, it is certain that it uses myriad of contextual cues that are present in a typical everyday scene. For example, even though two surfaces marked as A and B in Fig. 1 are equiluminant, the visual system estimates (correctly) that their lightnesses are different (also see Adelson, 2000; Blakeslee & McCourt, 2004; Goldstein, 2009; Purves & Lotto, 2011; Purves et al., 2008).

Now let us suppose that we superimpose grating patterns on these patches (see Fig. 4). What happens to the perceived contrast of those gratings? Vision scientists calculate the local contrast in an image using various formulas. (e.g., Michelson or Weber contrast). But these metrics do not always capture the relevant perceived qualities in the image (Haun & Peli, 2013). It is well known that perceived contrast of a simple isolated stimulus, such as a grating, is affected by its spatial frequency and background (or mean) luminance even when its calculated photometric contrast remains the same (e.g., Kane & Bertalmiío, 2016; Kilpeläinen, Nurminen, & Donner, 2011; Kilpeläinen, Nurminen, & Donner, 2012; Peli, Yang, Goldstein, & Reeves, 1991; Peli, Arend, & Labianca, 1996; Van & Bouman, 1967). In such simple configurations luminance and lightness covary. However as Fig. 1 convincingly demonstrates lightness and luminance do not always covary. Then the question arises: does the perceived contrast of a grating vary with the luminance or lightness of its background? Finding an answer to this question is critical to fully understand the underlying mechanisms of contrast perception, because it could indicate at which level contrast, luminance and lightness operate and interact in the visual system.

Even though context-dependent lightness has been studied extensively (e.g., Boyaci, Doerschner, Snyder, & Maloney, 2006; Gilchrist, 2015; Kingdom, 2011), its effects on perceived contrast were not studied directly and systematically previously. In a number of studies, related problems, particularly the effects of context-dependent lightness (and brightness) on luminance discrimination and detection thresholds were addressed (e.g., Hillis & Brainard, 2007; Maertens & Wichmann, 2013; Rieger & Gegenfurtner,

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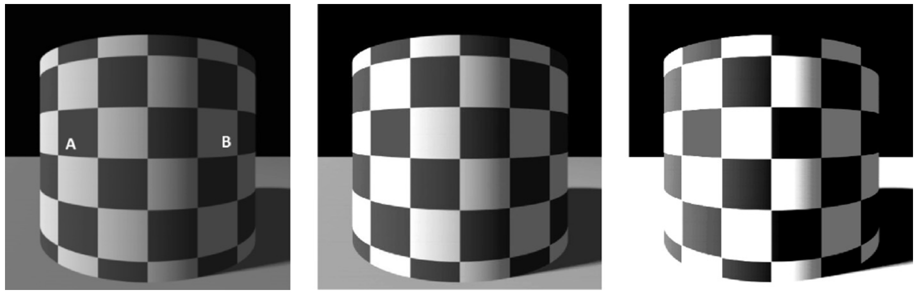

Fig. 1. Examples of the stimulus after image manipulations. "Context squares" (CSs), A and B in the first image and in the same position in all images, have identical luminance but different lightness.

1999, also see Kingdom, 2011; Singh & Anderson, 2002, for a general discussion of two-way interactions between contrast, and brightness and lightness). However to the best of our knowledge, there is no study directly investigating the effect of context-dependent lightness on perceived contrast and the interaction between contrast and luminance sub-systems.

Maertens, Wichmann, and Shapley (2015) investigated the effect of surrounding context on the lightness of elliptical regions using Adelson's cylinder-and-checkerboard stimulus (Adelson, 1995), and Shapley and Reid's stimulus (Shapley & Reid, 1985). In both types of context they placed elliptical targets on perceived-dark and perceived-light squares which were in fact equiluminant. They found that lightness of ellipses were assimilated, for example the ellipse placed on perceived-lighter square was also perceived lighter. However Maertens et al. (2015) did not asses perceived contrast between those ellipses and their background explicitly, in fact they offered models to explain their lightness results based on the photometric contrast values.

To directly examine the effect of context-dependent lightness on perceived contrast we conducted behavioral experiments using a stimulus inspired by Adelson's checkerboard stimulus (Adelson, 1995). There were two equiluminant context squares (CSs) on the stimulus, lightnesses of which appeared considerably different (Fig. 1). This stimulus allowed us to keep the luminance constant and test only the effect of context-dependent lightness. We had two main reasons for using this stimulus: firstly it leads to a very strong lightness effect, which increases our chances to find an empirical evidence for the effect of context-dependent lightness on perceived contrast. Secondly, in this configuration the target squares A and B are symmetrically positioned (they are not in Adelson's original stimulus), which makes better experimental conditions for future behavioral and neuroimaging studies that we are planning.

Firstly we assessed the lightness effect in the stimulus after applying several image manipulations. Results confirmed that the CSs differed statistically significantly in lightness for all observers. Another purpose of this experiment was to identify the image-manipulated stimuli that yield large lightness effects to use in the subsequent contrast experiments. In the second experiment we measured the perceived contrast of rectified square-wave gratings superimposed on the CSs (see Fig. 4). Using rectified gratings allowed us to study positive and negative contrast patterns independently, which was critical because both behavioral and neural evidence in previous studies suggest fundamental differences between processing of incremental and decremental luminance patterns (e.g., Blackwell, 1946; Chubb & Nam, 2000; Economou, Zdravkovic, & Gilchrist, 2007; Kremkow, Jin, Wang, & Alonso, 2016; Patel & Jones, 1968; Rekauzke et al., 2016; Rudd & Zemach, 2004, 2005; Sato, Motoyoshi, & Sato, 2016; Whittle, 1986; Zaghloul, Boahen, & Demb, 2003). Previous studies in literature have found interactions between spatial frequency and mean luminance in contrast perception using simple gratings (Chubb, Sperling, & Solomon, 1989; Georgeson & Sullivan, 1975; Peli et al., 1996; Robilotto & Zaidi, 2004; Van & Bouman, 1967). More specifically, perceived contrast of high-frequency gratings were more strongly affected by the mean luminance (Peli et al., 1996). Therefore, in our experiments we included spatial frequency as a further condition. Two more experiments were conducted to address possible confounds and the effect of luminance alone.

2. Experiment 1: measurement of the lightness effect

In the first experiment we quantified the lightness effect in the contextual stimulus after several image manipulations (Fig. 1). One of the main purposes of this experiment was to find the impact of image manipulations on the strength of the lightness effect. This allowed us to identify the stimuli with strong lightness effects to use in subsequent contrast experiments.

2.1. Methods

2.1.1. Participants

Eight participants including the author ZP participated in the experiment (three male). The mean age was approximately 23.4 ranging from 21 to 26. All participants reported normal or corrected-to-normal vision, and had no history of neurological or visual disorders. Participants gave their written informed consent and the experimental protocols were approved by the Human Ethics Committee of Bilkent University.

2.1.2. Stimuli, experimental procedure and analyses

The experimental software was prepared by us using the Java programming platform. The stimuli were presented on a CRT monitor (HP P1230, 22 inch, 1600 × 1200 resolution). Presentation of correct luminance values was ensured by using a gray scale look-up table prepared after direct measurements with a colorimeter (SpectroCAL, Cambridge Research Systems Ltd., UK). Participants were seated 75 cm from the monitor, and their heads were stabilized using a head-and-chin rest. Participants' responses were collected via a standard computer keyboard.

A variant of Adelson's checkerboard stimulus ("contextual stimulus" or "stimulus" from here on, Fig. 1) was generated using the open source rendering package Radiance (Larson & Shakespeare, 1998). The lightness effect is defined and quantified as the difference between the lightnesses of the context squares (CSs) marked "A" and "B" in Fig. 1. The stimulus subtended 9.5 by 9.5 degrees of visual angle. Approximate size of the CSs was 0.85 by 0.85 degrees of visual angle. We prepared eleven different versions of the stimulus by manipulating the overall image contrast and luminance using the open-source software GIMP (http://www.gimp.org/). After these image manipulations, luminance of the context squares were 1.64, 2.74, 2.86, 4.34, 6.58, 10.1, 12.65, 16.11, 17.4, 20.41 and 26.15 cd/m^2 (mean luminance of the stimulus: 1.83, 3.9, 5.13, 5.83, 6.98, 11.34, 13.18, 16.43, 16.74, 21.14, 23.37 cd/m^2, respectively). Because of the configuration of the stimulus the right context square was subjectively lighter than the left one (see Fig. 1 for examples).

Participants' task was to adjust the luminance of an external patch until its lightness matched that of the context squares. The matching patch was placed on a random-noise background, subtending 15 × 3 degrees of visual angle (Fig. 2). Luminance of each pixel on the random-noise background was drawn from a random distribution between 0 and maximum possible luminance of 100.32 cd/m^2, and the resulting image was convolved with a 6-by-6 uniform filtering kernel. The size of the matching patch was approximately the same as that of the context squares. The initial luminance of the matching patch was determined randomly at the beginning of each trial. Adjustments could be done in large steps (approximately 2 cd/m^2) using the right and left arrow keys or in smaller steps (approximately 0.2 cd/m^2) using the up and down arrow keys. Instructions about which context square is tested in that particular trial was given by the text strings "left" and "right" on the random-noise background. Each variant of the stimulus was presented five times for each context square. This resulted in 110 trials completed in one experimental session (11 stimulus versions (CS luminance levels) × 2 CS positions × 5 repetitions). The order of trials was randomized.

Data were analyzed using SPSS Version 19 (SPSS Inc., Chicago, IL). A repeated measures analysis of variance (ANOVA), was conducted in order to test two factors: CS luminance (11 levels), and CS position (two levels: left, right). Additionally, the magnitude of the lightness effect, quantified as the difference between right

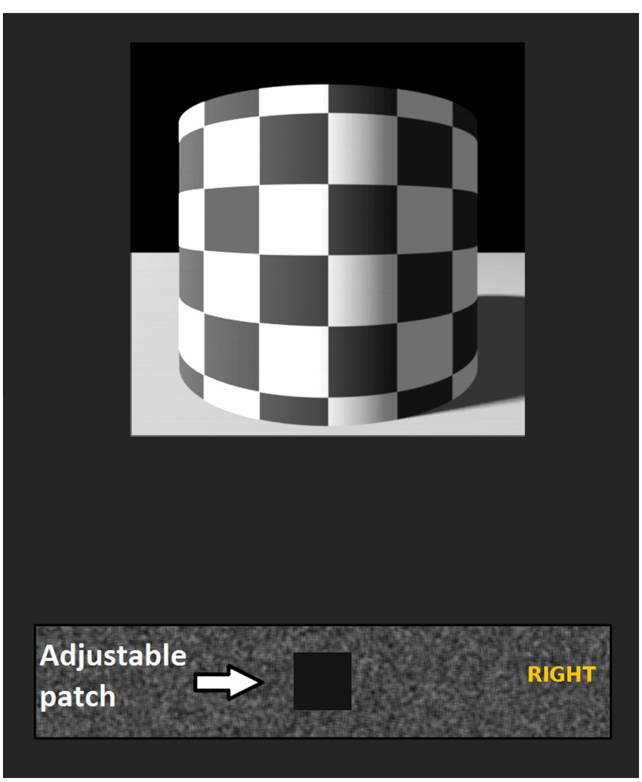

Fig. 2. Lightness experiment. Participants' task was to adjust the luminance of an external patch to match the lightness of the context squares. The arrow and the text "adjustable patch" were not shown on the screen during the experiment. Position of the context square under test was indicated with the texts "RIGHT" and "LEFT" displayed on the random noise background.

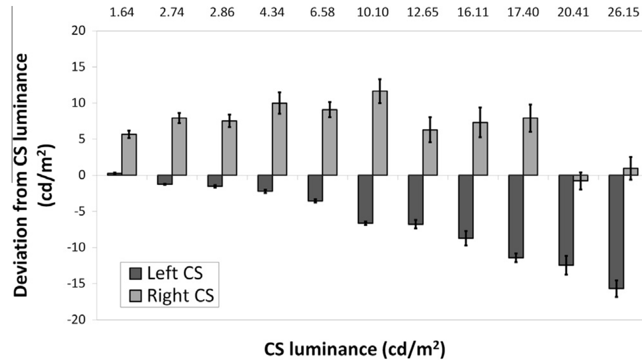

Fig. 3. Results of the lightness experiment. Deviation of settings from actual luminance is plotted for each CS position as a function of context square luminance. Positive (negative) deviation means setting was higher (lower) than the actual CS luminance. A value of "0" corresponds to perfect luminance match. Under all conditions, participants judged the right CS statistically significantly lighter, consistent with the subjective experience in Fig. 1. Error bars show ±SEM.

and left CS settings, was tested with two-tailed paired-samples Student's t-test for each level of CS luminance.

2.2. Results

Fig. 3 shows the deviation of the raw settings from the actual CS luminances. Analyses showed that main effect of CS position was statistically significant ($F(1,7) = 89.8$, $p < 0.001$). Mean deviation from the actual luminance for the right CS ($M = 6.68$, $SEM = 1.18$) was higher than that for the left CS ($M = -6.36$, $SEM = 0.37$). Two-tailed paired-samples Student's t-test results showed that settings for left CS and right CS were statistically significantly different at all luminance levels tested (among 11 conditions: minimum $t(7) = 6.37$; maximum $t(7) = 13.3$; mean $t(7) = 9.03$; $p < 0.001$ for all conditions). These results clearly show that, even though the CSs were equiluminant the right CS was perceived lighter, which is consistent with the subjective experience in Fig. 1. In addition, we found a main effect of the context square luminance ($F(10,70) = 59.06$, $p < 0.001$): as the luminance of context squares increased the lightness effect tended to increase.

2.3. Intermediate summary and discussion

In all conditions tested we found a significant effect of context on lightness, which slightly increased with CS luminance. Thus the lightness effect in our stimulus was so robust that we could utilize it to test the effect of context-dependent lightness on contrast perception. Because there was not a big difference in the lightness effect across different CS luminance values, we used four versions of the context stimulus in the following contrast experiments: one with a high, one with a medium, and two with low CS luminances. We included two low CS luminances because results of Peli et al. (1991) suggest that the effect of mean luminance on perceived contrast is stronger for lower luminances.

3. Experiment 2: measurement of perceived contrast

In this experiment, we investigated the relationship between context-dependent lightness and perceived contrast. For this purpose we used rectified gratings superimposed on CSs with positive contrast (incremental grating), and negative contrast (decremental grating, Fig. 4). We used four versions of the context stimulus that led to strong lightness effects based on the results of the first experiment as explained before.

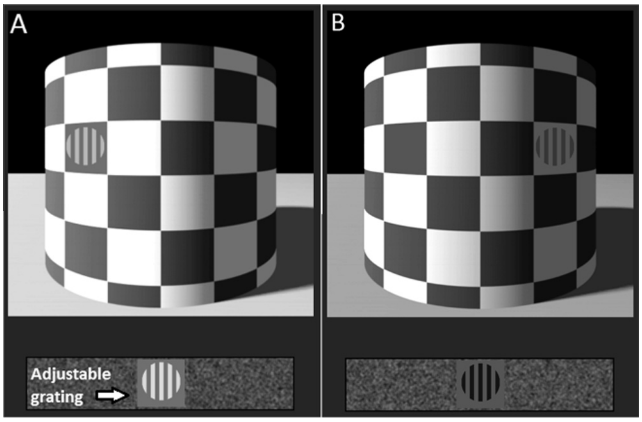

Fig. 4. Task and procedure in the contrast experiment. Participants were asked to adjust the contrast of a "match" grating to match that of the "standard". Standard was always placed on one of the CSs. The match was placed on a square, which was placed on a random-noise background. The arrow, and the text "adjustable grating" were not shown on the screen during the experiment. (A) Incremental grating condition, (B) decremental grating condition.

3.1. Methods

3.1.1. Participants

Incremental grating condition. Two males and four females participated in the experiment under the incremental grating condition. Two of them were among the participants of the lightness experiment and they also participated in the experiment under the decremenental grating condition. The mean age was 24.6 ranging from 22 to 29.

Decremental grating condition. Two males and four females participated in the experiment under the decremental grating condition. Two of them were among the participants of the lightness experiment and they also participated in the experiment under the incremental grating condition. The mean age was 25.3 ranging from 23 to 28.

All participants reported normal or corrected-to-normal vision, and had no history of neurological or visual disorders. Participants gave their written informed consent and the experimental procedures and protocols were approved by the Human Ethics Committee of Bilkent University.

3.1.2. Stimuli, experimental procedures and analyses

The contextual stimulus and the physical components of the experimental setup were the same as in the lightness experiment, except a bigger version of the context stimulus was used (13.4 by 13.4 degrees visual angle).

We estimated the perceived contrast of incremental and decremental rectified square-wave gratings superimposed on the CSs (Fig. 4). Our aim was to compare the perceived contrast of photometrically identical gratings superimposed on equiluminant but perceptually different CSs. Participants' task was to perceptually adjust the contrast of a "match" grating to match that of the "standard" grating. The standard was always placed on one of the CSs. The match grating was placed on a square that had the same luminance and approximately the same dimensions as the CS, which in turn was placed on an external random-noise background (Fig. 4). Contrast of the gratings was defined by Weber Contrast, $C = (L_{gr} - L_{CS})/L_{CS}$, where L_{gr} and L_{CS} correspond to grating and CS luminance respectively (Peli, 1990). The positive contrasts tested were 0.1, 0.3 and 0.6, and the negative contrasts were −0.1, −0.3 and −0.6. Adjustment was done in $\Delta C = 0.1$ steps by the use of left and right arrow keys and fine tuned adjustment was done in $\Delta C = 0.01$ steps using the up and down arrow keys. Four versions of the context stimulus were used, in which CS luminances (background luminance) were 1.64, 2.86, 10.1, and 17.4 cd/m^2.

Note that the mean luminance of CS-plus-grating slightly varied depending on the contrast of the grating superimposed on the CS. In Fig. 5 and 6 we plot results as a function of CS luminance alone. Stimuli were presented in a random order on a black background. Gratings with frequencies of 2.5, 5, and 10 cycle/degree were tested, blocked in different sessions. Match always had the same frequency as the standard. In each trial the contrast of the standard was pseudo-randomly chosen among the contrast levels tested and balanced across the session. Match had the same contrast polarity as the standard and its initial contrast was determined randomly at the start of each trial. During the trial the background luminance of the match remained constant and equal to that of the CSs. Thus, when the participants adjusted the contrast of the match grating the mean luminance of match background-plus-grating slightly varied. This may have a very small or negligible effect, which should not change the main conclusions because we always compare the settings for physically identical CSs. Each session contained 120 trials with 5 repetitions for every combination of conditions (4 stimulus versions (CS luminance) × 3 contrast levels × 2 CS positions × 5 repetitions).

The analyses were performed on an "effect score" defined by

$$\rho_C = \frac{C_R - C_L}{C_R + C_L}, \tag{1}$$

where C_R and C_L stand for the participant's setting for the grating superimposed on the right and left CS respectively. An effect score of zero would mean no difference in perceived contrast between the gratings. For decremental contrasts, before computing ρ_C we first converted the contrast settings to positive values (therefore a positive ρ_C means perceived contrast on the right CS is more negative in the case of decremental gratings). In order to test whether the effect score is different than "0" we conducted one-sample two-tailed Student's t-test in SPSS. Effect scores obtained under different contrast types were compared using a two-tailed independent-samples t-test in SPSS. Further analyses were conducted using a repeated measures ANOVA with three factors (luminance, frequency, and contrast) and Bonferroni corrected pairwise comparisons in SPSS.

3.2. Results

Raw settings are shown in Fig. 5 and the effect scores are shown in Fig. 6. In the incremental grating condition, mean effect score was positive ($\bar{\rho}_C = 0.14$, SEM = 0.02), and statistically significantly different than zero ($t(5) = 8.03$, $p < 0.01$). In other words, perceived contrast was higher when the grating was located on the perceptually lighter right CS. In the decremental grating condition mean effect score was negative ($\bar{\rho}_C = -0.01$, SEM = 0.02). However, it was not statistically significantly different than zero ($t(5) = -0.52$, $p > 0.05$). In other words, there was no difference between perceived contrast of decremental gratings superimposed on the left and right CS. Effect scores for incremental and decremental gratings were statistically significantly different ($t(10) = 5.48$, $p < 0.01$). There was no significant main effect of frequency on the results in either condition (incremental grating: $F(2,10) = 0.1$, $p > 0.05$; decremental grating: $F(2,10) = 1.02$, $p > 0.05$). Therefore Fig. 6 shows the effect scores averaged across frequencies.

CS luminance affected ρ_C in both conditions (incremental grating: ($F(3,15) = 10.6$, $p < 0.05$; decremental grating: $F(3,15) = 6.72$, $p < 0.05$)). We did not find an effect of standard contrast in the incremental grating condition ($F(2,10) = 2.85$, $p > 0.05$). However,

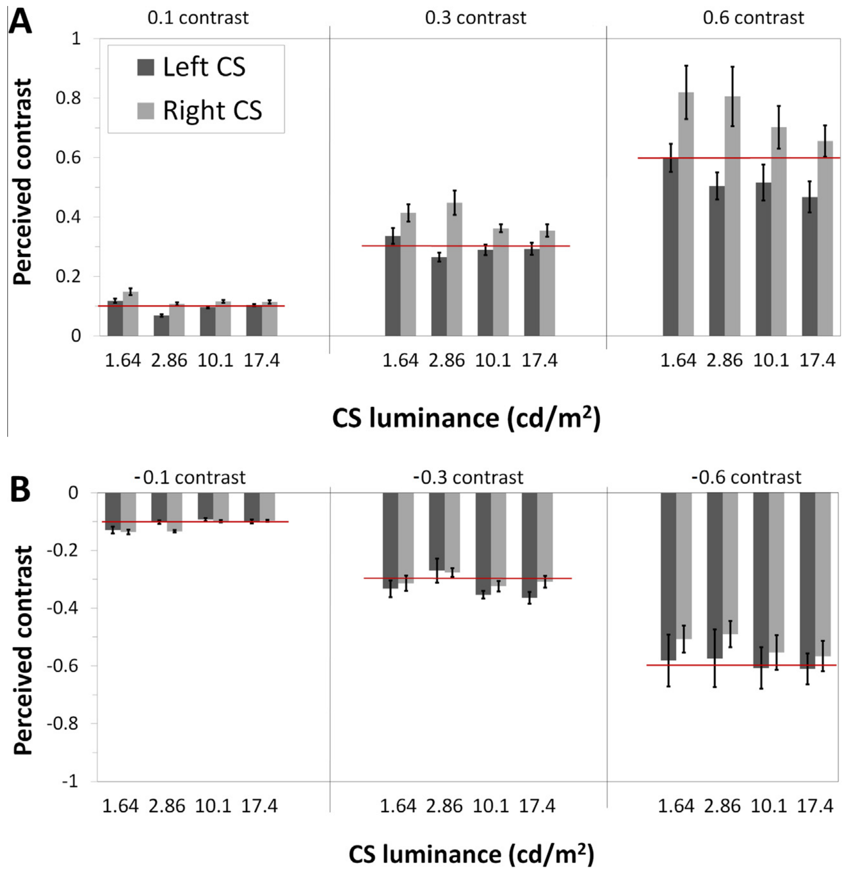

Fig. 5. Mean settings in the contrast experiment. Red horizontal lines shows the actual contrast under that condition. (A) Incremental grating condition. (B) Decremental grating condition.

standard contrast affected ρ_C in the decremental grating condition ($F(2,10) = 12.21$, $p < 0.05$).

3.3. Intermediate summary and discussion

Results of this experiment show that context-dependent lightness affects perceived contrast of an incremental grating: the same grating appears to have higher contrast when it is superimposed on an equiluminant but perceived-lighter background. This result is in line with previous findings, which demonstrated that perceived contrast is higher for gratings with higher mean luminance even when their photometric contrast remains constant (e.g., Peli et al., 1991, 1996). However, interestingly we found no effect of context-dependent lightness for decremental gratings. There was no main effect of spatial frequency, which is not completely in line with previous studies (e.g., Peli et al., 1996). This discrepancy will be addressed in more detail in the general discussion section below.

4. Experiment 3: perceived contrast on isolated patches

In the previous experiment we found that context-dependent lightness of a patch affects the perceived contrast of incremental gratings superimposed on it. In this experiment we examine how luminance of isolated patches affect the perceived contrast, thereby directly compare the effects of luminance and context-dependent lightness. Results are also compared to the findings of Peli et al. (1991), where mean or background luminance was shown to have an effect on perceived contrast.

4.1. Methods

4.1.1. Participants

The same participants (four female, two male) who took part in Experiment 2 under decremental grating condition participated in this experiment. Participants gave their written informed consent and the experimental procedures and protocols were approved by the Human Ethics Committee of Bilkent University.

4.1.2. Stimuli, experimental procedures and analyses

In this experiment we measured the perceived contrast of gratings superimposed on a pair of gray-scale patches without the three-dimensional context. Two patches were located at the same spatial positions and dimensions as the CSs in Experiment 2. Luminances of the isolated patches were different and they were determined based on the group average results of the lightness experiment (Experiment 1) to approximate the perceptual difference between the CSs. More specifically the left patch had a lower and the right patch had a higher luminance. Four pairs of luminances were used, corresponding to the CS luminances of 1.64, 2.86, 10.1, or 17.4 cd/m^2 (note that this is the same set of luminance values used in Experiment 2). For example, for the CS luminance of 1.64 cd/m^2, we used 1.92 cd/m^2 for the left and 7.3 cd/m^2 for the right patch, as these were the average settings obtained in the lightness experiment for the left and right CSs respectively. Other luminance pairs were as follows: 1.33, and 10.39 cd/m^2; 3.46, and 21.75 cd/m^2; 5.98, and 25.33 cd/m^2. A match grating was superimposed on a patch with a luminance that corresponded to the tested patches in that trial (1.64, 2.86, 10.1, or 17.4 cd/m^2),

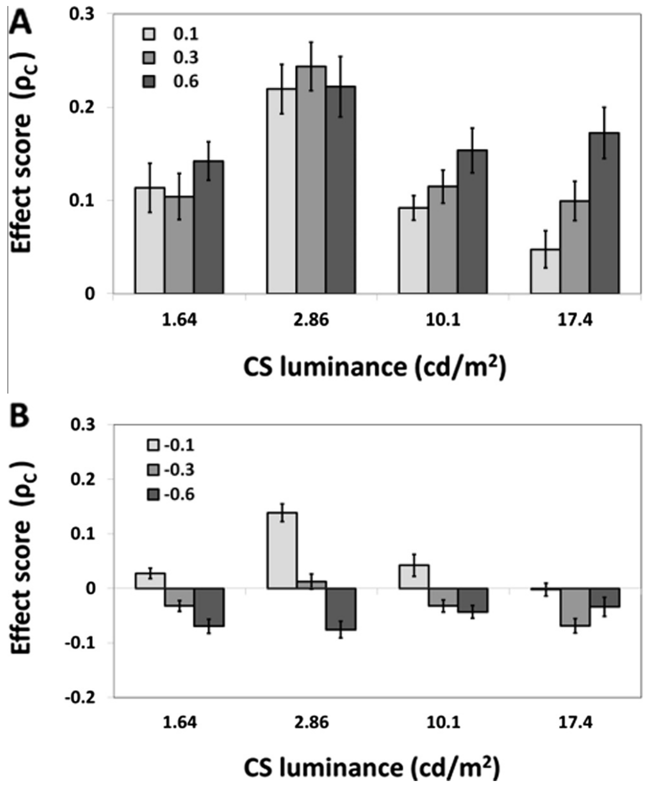

Fig. 6. Mean effect scores, $\bar{\rho}_C$, from the contrast experiment. Brightness of the bars indicate different contrast levels. Because frequency did not have a main effect, effect scores are averaged over three frequency levels. An effect score of "0" means that there is no difference between perceived contrasts of the gratings superimposed on the right and left CSs. A positive (negative) value means that the absolute value of the perceived contrast of the grating on the right CS was greater (less) than that on the left. (A) Incremental grating condition. (B) Decremental grating condition.

which in turn was placed on an external random-noise background. Participants' task was to adjust the contrast of the match grating to match that of the standard grating. The standard grating was pseudo-randomly superimposed on one of the two patches, and its contrast could be 0.1, 0.3, or 0.6 in the incremental grating condition, and −0.1, −0.3, or −0.6 in the decremental grating condition. The initial contrast of the match was determined randomly at the start of each trial. Both match and standard gratings had a spatial frequency of 2.5 cycle/degree. There were 120 trials (4 luminance pairs × 3 contrast levels × 2 patch positions × 5 repetitions) in each session. Participants completed two sessions, one for incremental gratings and one for decremental gratings.

Raw data were converted to effect scores as defined before (see Eq. (1)). For the decremental gratings, before computing ρ_C we first converted the contrast settings to positive values (therefore in case of decremental gratings a positive score means that perceived contrast on the right (higher luminance) patch is more negative). All further analyses were performed on the effect scores. A two-tailed one-sample t-test was conducted to test whether the effect score is different than zero. In order to determine the effect of other factors (luminance pair and contrast), a repeated measures ANOVA was applied. Incremental and decremental grating conditions were compared using two-tailed paired-samples t-tests. Finally,two-tailed independent-samples t-tests (for incremental gratings) and two-tailed paired-samples t-tests (for decremental gratings) were employed to compare the effect scores with those in Experiment 2.

4.2. Results

Results are shown in Fig. 7. Under the incremental grating condition the mean effect score was positive ($\bar{\rho}_C = 0.2$, SEM = 0.03) and statistically significantly different than zero ($t(5) = 6.08$, $p < 0.01$), which means perceived contrast was higher when the grating is placed on a higher luminance background. However, under the decremental grating condition the mean effect score was not statistically significantly different than zero ($\bar{\rho}_C = 0.05$, SEM = 0.02; $t(5) = 1.93$, $p > 0.05$). The difference between the effect scores for incremental and decremental gratings was statistically significant ($t(5) = 3.07$, $p < 0.05$).

Next we compared the results with those from Experiment 2. For incremental gratings there was not a significant difference between the effect scores ($t(10) = 1.23$, $p > 0.05$). Overall, effect scores tended to be larger for isolated patches with different luminance (2.5 cycle/degree condition on CSs: $\bar{\rho}_C = 0.15$, SEM = 0.03; on isolated patches: $\bar{\rho}_C = 0.2$, SEM = 0.03). For the decremental gratings the difference was statistically significant ($t(5) = 2.73$, $p < 0.05$; 2.5 cycle/degree condition on CSs: $\bar{\rho}_C = -0.02$, SEM = 0.03; on isolated patches: $\bar{\rho}_C = 0.05$, SEM = 0.02).

4.3. Intermediate summary and discussion

Results show that background luminance affects perceived contrast of incremental gratings, which is inline with previous literature (e.g., Peli et al., 1991). However, there was no effect of luminance on the perceived contrast of decremental gratings. The pattern of results is consistent with Experiment 2, although in general the effect of luminance tends to be larger than that of context-dependent lightness.

5. Experiment 4: lightness of the gratings

In Experiment 2, where gratings were superimposed on CSs, participants could have used a strategy where they match the lightness of gratings to perform the task, instead of matching their contrast. In order to rule out this possibility and to ensure that participants indeed performed the given contrast task we conducted a control experiment. Here we asked the participants to estimate the lightness of incremental gratings superimposed on CSs in the contextual stimulus. We then used these estimates to calculate "derived contrast" and "derived effect score" as described below. Finally we compared the derived scores to those obtained in Experiment 2.

5.1. Methods

5.1.1. Participants

The same six participants who participated in Experiment 2 incremental grating condition completed this experiment. Participants gave their written informed consent and the experimental procedures and protocols were approved by the Human Ethics Committee of Bilkent University.

5.1.2. Stimuli, experimental procedures and analyses

A standard grating with one of 0.1, 0.3, or 0.6 Weber contrast was superimposed on one of the CSs in a pseudo-random order. Participants' task was to adjust the luminance of an external circular matching patch to match the gratings in lightness (*i.e.,* the vertical "bars"). The match was placed on a square that had the same luminance as the CS and approximately the same dimensions, which in turn was placed on an external random-noise background (Fig. 8). Results from this experiment were converted first to "derived contrast" by placing participants' estimate, $\widehat{L}_{gr}$, in the

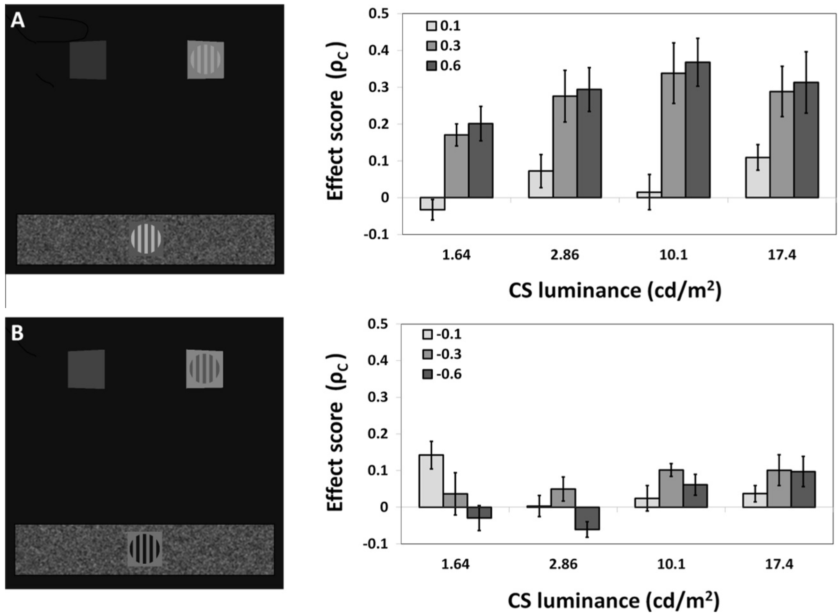

Fig. 7. Perceived contrast of gratings on isolated backgrounds. Experimental design and results. Participants adjusted the contrast of the match grating to match that of the standard on isolated patches. The geometry and position of the patches were identical to those of the CSs in the contextual stimulus. However this time the patches actually differed in luminance. (A) Incremental gratings. (B) Decremental gratings. The two bar plots on the right show the results presented in the same format as in Fig. 6. The pattern of results was similar to the one found in Experiment 2.

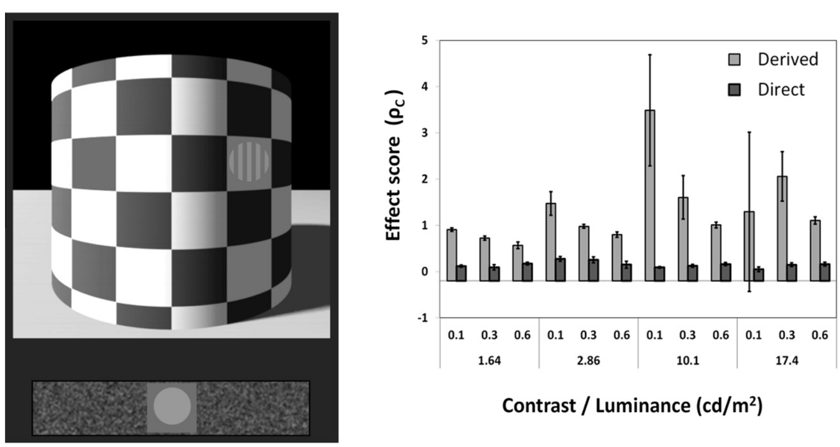

Fig. 8. Lightness of the gratings. In this experiment participants matched the lightness of the gratings using an external circular match placed on a patch and random noise background. "Derived contrast" and "derived effect score" were computed using those estimates. Derived effect scores and the effect scores from Experiment 2 are shown in the right panel. Clearly, participants performed the two tasks differently.

contrast equation, $C = (L_{gr} - L_{CS})/L_{CS}$. Next "derived effect scores" were computed using Eq. (1), based on the derived contrast values, and compared with the results from Experiment 2 using two-tailed paired-samples Student's t-test.

5.2. Results

Results are shown in Fig. 8. We found that derived effect scores of this experiment and those obtained in Experiment 2 were statistically significantly, and extremely different (overall difference: $t(5) = 23.37$, $p < 0.001$). For instance, for the CS with a luminance of 2.86 cd/m^2 and grating with a contrast of 0.3, the effect score was 0.25 in Experiment 2, whereas here the derived effect score was 0.97 (Fig. 8). These results show that if participants were simply matching the lightness of gratings without considering contrast at all, we would obtain extremely different results for the contrast matching experiments. Thus, the results provide a strong evidence that participants matched the contrasts of gratings, not their lightnesses in the contrast experiments.

6. Discussion

We investigated how the perceived contrast of rectified square-wave gratings is affected by the luminance and context-dependent lightness of its background. In our experiments we used a stimulus in which two equiluminant "context squares" (CSs) appeared different in lightness (Fig. 1). First in a behavioral experiment we ensured that the stimulus had the desired lightness effect on all participants. In the second experiment, we measured the perceived contrast of incremental and decremental rectified square-wave gratings superimposed on the CSs. We found that perceived contrast increased with context-dependent lightness of the background for incremental gratings, but not for decremental gratings. More specifically, when identical gratings are superimposed on equiluminant backgrounds, the one on the perceived-lighter background appeared to have higher contrast. In the next experiment we measured the perceived contrast of gratings superimposed on isolated patches with different luminances. The pattern of results were consistent with the previous experiment: perceived contrast increased with background luminance for incremental but not decremental gratings.

Our results are consistent with previous studies which showed that perceived contrast of visual patterns in simple scenes, such as Gabor patches on a uniform background vary with their mean or background luminance (e.g., Peli, 1995; Peli et al., 1991, 1996). Here we show that the effect is not limited to the background luminance but extends to context-dependent lightness. Moreover, in our study we show that even when there is no physical difference between the patterns there is still an effect of background lightness on perceived contrast. Comparing physically identical patterns circumvents nonlinearities and confounds that might in principle be introduced by physical changes.

Surprisingly, luminance and context-dependent lightness of the background affected the perceived contrast of incremental gratings but not decremental ones. Asymmetries between positive and negative contrast patterns were studied before. For example, it has been shown that detection threshold of decrement is lower than that of increment particularly when the background luminance is low (e.g., Blackwell, 1946; Patel & Jones, 1968; Short, 1966). However perceived contrast of decremental gratings were not systematically studied previously under conditions similar to those reported here. Processing differences between positive and negative local contrast has been reported in literature both by behavioral and neuronal studies (e.g., Chubb & Nam, 2000; Rekauzke et al., 2016; Rudd & Zemach, 2004, 2005; Sato et al., 2016; Whittle, 1986; Zaghloul et al., 2003). The light–dark asymmetry is also incorporated in some models of brightness (e.g., Rudd, 2013, 2014). Yeh, Xing, and Shapley (2009) found that single-unit activity of V1 neurons was stronger for decrements than increments. In a human fMRI study Olman, Boyaci, Fang, and Doerschner (2008) reported stronger BOLD signal in V1 in response to negative contrast stimuli compared to positive contrast ones. Komban, Alonso, and Zaidi (2011) showed that dark targets are perceived faster and more accurately than light targets at suprathreshold levels on noisy backgrounds and argued that this difference indicates that greater neuronal resources are devoted to process decremental patterns in the early visual pathway. Therefore, the asymmetry found in our study could be the consequence of differentiation in the processing of positive and negative contrast by the visual system, starting from the retinal ganglion cells (Chichilnisky & Kalmar, 2002). Note that, it is also possible that any effect of luminance or context-dependent lightness on perceived contrast of decremental patterns could have gone undetected in our experiments because of limited range of background luminances and lightnesses studied. Particularly for the isolated patches there was a trend for the effect of luminance on perceived contrast that did not reach a statistically significant level.

It is well known that spatial frequency affects contrast perception in simple gratings (e.g., Campbell & Robson, 1968; Chubb et al., 1989; Georgeson & Sullivan, 1975; Peli et al., 1996; Robilotto & Zaidi, 2004; Van & Bouman, 1967). For all frequencies tested we found an effect of context-dependent background lightness on perceived contrast, however there was no influence of frequency on the magnitude of the effect. This result does not seem to be in complete agreement with the findings of Peli et al. (1996), who showed that perceived contrast of high frequency gratings (e.g., 8 and 16 cycle/degree) are strongly affected by background luminance, whereas that of low-frequency gratings (e.g., 1 and 2 cycle/degree) are much less affected. The disagreement could simply be caused by differences in experimental procedures. The patterns used by Peli et al. (1996) were sinusoidal Gabor patches with up to 16-fold difference in spatial frequency (1 through 16 c/d), whereas here we used rectified square-wave gratings with a maximum of 4-fold difference in spatial frequency. In Peli et al. (1996) study participants altered their gaze between two patterns every 1.5 s, whereas in our study they freely viewed the stimulus. Moreover, Peli et al. (1996) used a standard grating whose spatial frequency was fixed, and the spatial frequency of their test patch varied. In our study the spatial frequencies of the standard and the match patch were equal in each trial. Therefore we did not directly compare perceived contrast across different frequencies. Instead we compared the magnitude of the effect of background lightness on perceived contrast for different spatial frequencies. Alternatively the disagreement with Peli et al. (1996) results could be an indication that lightness and context-dependent lightness of the background affect perceived contrast through different mechanisms. However, in an earlier pilot study using isolated patches we failed to find an effect of frequency, which does not support such a possibility.

Previously Hillis and Brainard (2007), Maertens and Wichmann (2013) and Maertens et al. (2015) showed that lightness of incremental elliptic targets was affected by the context-dependent lightness of their otherwise equiluminant backgrounds. Could our results be simply explained by a purely lightness-based contrast mechanism, in which first the lightness of each pixel is estimated, and based on this the contrast is computed? Results of our control experiment do not support this conjecture. The contrast of incremental gratings computed mathematically based on participants' lightness estimates were extremely different than their perceived contrasts directly measured.

Our results also highlight that simply keeping photometric contrast constant does not guarantee the same for the perceived contrast. This is often overlooked in lightness literature, and in some studies perceived contrast may have led to the reported lightness effects (e.g., Hillis & Brainard, 2007; Maertens & Wichmann, 2013; Maertens et al., 2015).

7. Conclusions

Results of this study show that perceived contrast is not determined solely by the localized features of the retinal image. Context-dependent lightness, as well as actual luminance, of the background influence the perceived contrast of rectified gratings. These results show that perceived contrast depends neither purely on luminance nor lightness (Guth, 1973), instead they suggest that luminance and lightness, and contrast share common underlying mechanisms but can be assessed independently at least to some extent (Dai & Wang, 2012; Geisler, Albrecht, & Crane, 2007; Mante, Frazor, Bonin, Geisler, & Carandini, 2005). Several neuronal mechanisms could potentially account for our findings. It is possible that in complex scenes perceived contrast is determined at a later stage and in a higher cortical area in the hierarchy of the visual system, after lightness is computed based on global information. Alternatively, perceived contrast could be determined in earlier areas, for example in primary visual cortex (V1), after receiving feedback about context-dependent lightness. The latter is plausible given recent results in literature showing context-dependent lightness related activity in early visual areas (e.g., Boyaci, Fang, Murray, & Kersten, 2007). In yet another alternative, the perceived contrast could be influenced directly by the context without lightness mediating the effect. With our current experimental design we cannot rule out this possibility either.

Our results show that perceived contrast of gratings are affected by the luminance and context-dependent lightness of their background in a very similar way. This strongly suggests that they share common underlying mechanisms. However we cannot currently explain why and how patterns presented on higher lightness, as well as luminance backgrounds should appear to have higher contrast. Likewise, we do not have any explanation for the asymmetry between perceived contrast of incremental and decremental gratings. Why should the visual system rely more on the photometric contrast when it comes to decremental patterns? This could have adaptive advantages considering the statistics of natural scenes (Elder, Victor, & Zucker, 2016). For example, measuring local contrast values (Benton & Johnston, 1999) showed that negative polarity noise has a wider distribution of local contrast values than positive polarity noise. However a complete answer is still beyond our grasp.

In this study we investigated the appearance of gratings, not their detection or discrimination. Hillis and Brainard (2007) previously showed that detection, discrimination and identification of incremental elliptical patches in complex scenes similar to ours were mediated by different mechanisms. Thus, it remains an open question as to how context-dependent lightness would affect detection and discrimination thresholds of contrast gratings. The other open question concerns the underlying neuronal mechanisms of the effects we found. As highlighted above, multiple cortical models could potentially explain the findings. To identify the correct model, further behavioral, and neuronal experiments are needed.

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